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Spring crops in three year rotations reduce weed pressure in winter wheat

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ABSTRACT

Downy brome (*Bromus tectorum* L.) is a problematic weed for the conventional fallow/winter wheat (F/W) production system in the low precipitation-region (< 350 mm yr^{-1}) of the Pacific Northwest. A 4-yr field experiment was conducted to determine if incorporating spring barley (B, *Hordeum vulgare* L.) or spring carinata (C, *Brassica carinata* A. Braun) into 3-yr crop rotations with W would benefit weed management. The experimental design was a split-plot with four replications where each phase was present every year for the following rotations: 1) F/W, 2) F/W/B, and 3) F/W/C. Reduced tillage, consisting of a single undercutting operation with a wide-blade sweep, and herbicides were used to control weeds during the fallow period. The seeded plots were subdivided in three different weed management areas: a weed-free area where weeds were pulled by hand, a weedy area with no weed control and a general area where weeds were chemically controlled. Weed density and cover per species and W yield were evaluated in each rotation. Grass cover and density after one and two complete cropping cycles were significantly higher in F/W than in F/W/B and F/W/C. Reduction in density and cover of total weeds was found after two cycles. However, differences in community biodiversity were only found between F/W, and F/W/B or F/W/C in 2017. Winter wheat plots of F/W had more downy brome than F/W/B or F/W/C indicating the greater capacity of the latter to control this weed. In 2018, the 3-yr rotation with barley had greater winter wheat grain yield compared with F/W when weeds were not present though weeds were more competitive in F/W/B. Intensifying the F/W cropping system into a 3-yr crop rotation of W followed by spring barley or spring carinata may reduce weed infestations of winter annual grasses that are difficult to control in W and the most competitive due to larger similarities in their life cycle with this crop.

1. Introduction

Historically, winter wheat (W, *Triticum aestivum* L.) has been sown in the inland Pacific Northwest, USA (Schillinger, 2016; Smiley et al., 2005) in a 2-yr rotation with fallow (F). Under low annual rainfall (< 350 mm), fallow is necessary to recharge soil moisture (Papendick, 2004; Young and Thorne, 2004) and maximize W yield in the following year (Schillinger and Young, 2004; Wuest and Schillinger, 2011). To prevent wind erosion, conventional fallow management with intensive tillage may be replaced with reduced tillage fallow consisting of a single undercutting operation with a wide-blade sweep (Locke and Bryson, 1997). Reduced tillage fallow has shown higher yields compared to no-till in F/W systems in the region (Schillinger, 2016). With reduced tillage fallow, farmers have had to rely on herbicides for weed control more than in conventional fallow management. Reliance on chemical products has led to herbicide resistance problems (Norsworthy et al., 2012). Prevalent weeds in the PNW, such as kochia (*Kochia scoparia* (L.) Schrad.), prickly lettuce (*Lactuca serriola* L.), downy brome (*Bromus tectorum* L.), and Russian thistle (*Salsola tragus* L.) are resistant to sulphonylurea-type herbicides in this region (Heap, 2016).

By reducing the abundance of dominant weed species, cropping system diversification is a weed control practice proven to be effective in reducing the reliance on herbicides (Angus et al., 2015; Davis et al., 2012; Kirkegaard et al., 2008; Liebman and Dyck, 1993). Cropping systems that include diverse crops (i.e., cereal, oilseed, or legumes) facilitate the use of herbicides with different modes of action and thus reduce the risk of resistance development (Blackshaw et al., 2002). Crop diversification as an adequate practice for weed control has been scarcely assessed in dryland wheat production systems of the Columbia Plateau (Lyon and Baltensperger, 1995; Young et al., 2016).

Oilseed crops are an attractive option for crop diversification in the Great Plains (Nielsen, 1998; Pavlista et al., 2016) and Columbia Plateau (Long et al., 2016; Pan et al., 2016; Sowers et al., 2012) of the U.S. Oilseed crops from *Brassicaceae* family provide vegetable oil for culinary and industrial uses, but also satisfy an emerging market for biofuels (Gesch et al., 2015). *Brassica napus* L. is a popular oilseed crop

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having both food and industrial utilities. Ethiopian spring mustard (C, *Brassica carinata* A. Braun), hereafter referred to as carinata, is an industrial oilseed that is ideally suited as a feedstock for production of lubricants and biofuels (Pan et al., 2012, Taylor et al., 2010). Yields of different *Brassica* oilseed crops could depend on the place in which each crop is established (Gesch et al., 2015).

Oilseed crops of *Brassica* species planted in rotation with cereal crops provide several benefits, due to the break-crop effect caused by the broadleaf crop (Angus et al., 2011; Kirkegaard et al., 2008). Higher W yields were found when diversifying with *Brassica* oilseed crops versus yields when W was preceded by another W crop (Angus et al., 2011; Bushong et al., 2012; Gan et al., 2003; Johnston et al., 2002). Moreover, areas where wheat cropping systems are established are also the ones with greater potential to introduce *Brassica* crops (Pavlista et al., 2011). Including *Brassica* crops in cereal cropping systems may also improve soil structure and nitrogen (N) cycling (Chan and Heenan, 1996; Ryan et al., 2006), enhance water and N use by the following wheat crop (Kirkegaard et al., 2001, 1994), and reduce weed and pathogen pressure (Kirkegaard et al., 2008).

The introduction of spring canola (*B. rapa* L. or *B. napus* L.) in a W cropping system decreased downy brome presence (Blackshaw, 1994), which is a serious problem in W because of its similar life cycle (Blackshaw et al., 2001). To control downy brome, the “break-crop effect” might be more effective in oilseed crops than in spring cereals because of greater availability of herbicides against this species in broadleaved oilseed crops (Blackshaw, 1994). Moreover, changes in weed seedbank composition depend on crop sequence (Bohan et al., 2011; Cousens et al., 2002; Dorado et al., 1999). Ball (1992) found that crop sequence was the most important factor influencing the seed bank partly due to different herbicides and tillage practices used in each crop, producing a shift in the seedbank favoring non-target weed species by herbicides or tillage operations. Oilseed radish (*Raphanus sativus* L. var. *oleifera*) was found to be more effective than glyphosate in controlling weeds following W (Samson, 1991).

Increasing crop competition for resources is another cultural weed control practice. For example, when canola is well established, seedlings grow and close canopy rapidly, competing well with annual weeds (Long et al., 2016). Spring barley (B, *Hordeum vulgare* L.) is reported to be more competitive than spring wheat against weeds (Blackshaw et al., 2002). Beres et al (2010) in western Canada found spring barley was the most effective cereal to suppress broadleaved weeds whereas Angus et al. (2015) in western Australia found no benefit because of similar biology, root-diseases and nutrition. Elsewhere, cereals such as oats (*Avena sativa* L.), triticale (× *Triticosecale* Wittm. ex A. Camus.), and barley all provided significant break-crop benefits to wheat (Kirkegaard and Ryan, 2014). Barley was also found to suppress soil root-lesion caused by pathogens in wheat crops (Smiley and Machado, 2009) by allelochemical exudation from its roots (Fay and Duke, 1977), which could contribute to weed control as well. As an aside, spring tillage or other weed control practices are possible when planting a spring crop and weeds can be controlled in their most susceptible stage (Liebman and Dyck, 1993). The seasonality of the crop could also be related to the predominant weed species. Moyer et al. (1994) found that winter annual weeds proliferated in winter crops and summer annual weeds were predominant in spring crops.

Information is lacking whether B or C could benefit weed management when introduced as spring crops in W-based systems of the PNW. The hypothesis of this study was that including a spring crop in the W-fallow system could reduce the weed infestation in the W phase, particularly winter annual species, and help with the control of resistant weeds. In addition, improvement in weed management could increase W yields and decrease weed control inputs thereby encouraging growers to intensify their fallow-based cropping systems in the PNW region. Therefore, the objectives of this study were to 1) evaluate the influence of intensification of the W-F system with a spring crop (B or C) on changes in abundance, diversity, and composition of weeds over time; and 2) determine differences in W yield and their relationship with weeds in the 3-yr cropping systems compared with the more traditional 2-yr cropping system. Spring barley was selected for this study because of its great competitiveness and drought resistance (Blackshaw et al., 2002). Spring carinata was selected because it is reported to have high weed competitiveness due to its bushy growth habit (Leon et al., 2017). Barley and many *Brassica* crops are already grown in the region. In Oregon alone, 45,000 and 4,000 ha were planted to barley and canola in 2016 (USDA, 2017).

2. Materials and methods

2.1. Site description

The 4-yr (2014-18) field experiment was conducted in a 6-ha field near Echo, Oregon, USA (45.7207 °N. Lat., -119.0483 °W. Lon.). The soil is a well-drained Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) with a surface soil pH of 5.9. Monthly mean temperature was computed from hourly measurements collected at a standard weather station located at the study site (Supplemental Fig. 1). Daily measurements of precipitation were obtained with a tipping bucket rain gauge at the site and used to compile the total precipitation for each month. Total annual precipitation from September to August was 273 mm in 2014-15, 262 mm in 2015-16, 327 mm in 2016-17, and 247 mm in 2017-18.

2.2. Experimental design and field operations

The experimental design accommodated three wheat-based cropping systems: F/W, F/W/B, and F/W/C that were first established in 2014. The 2-yr system (F/W) was used as a control. The experimental design was a split-block design with four replications or blocks. Each phase of the cropping system (i.e., W, B or C, and F) was present every season (Supplemental Table 1) bringing the total number of plots to 32 per season (eight plots per block). Individual plots were 30.5 m × 6.1 m (100 ft × 20 ft). Seeded plots (i.e., W, B and C) were subdivided into three areas: i) a weedy area (6.1 m × 3.05 m) where no weed control was applied, ii) a weed free area (6.1 m × 3.05 m) where weeds were pulled by hand, and iii) a general area (6.1 m × 24.4 m) where weeds were managed with post-emergence herbicides commonly used in the region. However, general areas planted to C did not have post-emergence herbicide control because no herbicides are registered in Oregon for that crop. Herbicide applications in W and B (Table 1) were performed during spring and summer with a self-propelled sprayer delivering 187 l ha^{-1} of product.

The fallow phase consisted of one pass with an undercutter V-blade sweep in early summer at a depth of 13 cm and subsequent chemical application with glyphosate and other herbicides. This “reduced tillage” fallow is less susceptible to wind erosion than traditional summer fallow involving multiple tillage passes with a cultivator. After harvest, all plots were treated with paraquat (*N*, *N′*-dimethyl-4,4′-bipyridinium dichloride) to control late-season broadleaf weeds that re-grow. Herbicides were applied using a self-propelled sprayer with 6-m spray boom delivering 93.6 l ha^{-1}.

Winter wheat plots were seeded with soft white cultivars Bobtail (in 2014, 2016 and 2017) and Ovation (in 2015). Spring barley plots were seeded with Champion cultivar. Carinata plots were seeded with cultivars AAC A110 and 080814 EM. Winter wheat was seeded at the 2.5 cm depth at a 30 cm row spacing on 30 November 2014, 13 October 2015, 16 October 2016, and 6 October 2017. Seed density was 132 kg ha^{-1} in 2014, 127 kg ha^{-1} in 2015, 119 kg ha^{-1} in 2016 kg ha^{-1}, and 99 kg ha^{-1} in 2017. Spring crops (barley and carinata) were seeded on 12 March 2015, 8 March 2016, 3 April 2017, and 15 March 2018 with a 30 cm row spacing. Barley seed density for barley was 130 kg ha^{-1} in 2015, 126 kg ha^{-1} in 2016, and 127 kg ha^{-1} in 2017 and 2018. Carinata seed density was 5.7 kg ha^{-1} in 2015 and 2016, 5.4 kg ha^{-1} in

Table 1
Herbicide applications in the general area of plots of winter wheat (W), spring barley (B), and spring carinata (C).

Year	Date	Crop plots	Description
2015	Feb 17 [a]	C	Glyphosate (Gly Star Plus®) at 1684 g ai ha^{-1}
	Mar 30	W	MCPA + bromoxynil (Vendetta®) at 1536 g ai ha^{-1}
			Thifensulfuron + tribenuron methyl (Harmony® Extra SG) at 18.3 g ai ha^{-1}
	May 18	B	MCPA + bromoxynil (Vendetta®) at 1200 g ai ha^{-1}
			Thifensulfuron + tribenuron methyl (Harmony® Extra SG) at 18.3 g ai ha^{-1}
	Aug 6	W/B/C	Paraquat dichloride (Paraquat Concentrate) at 3735 g ai ha^{-1}
2016	Feb 26 [a]	B/C	Glyphosate (Roundup Power Max®) at 3081 g ai ha^{-1}
			Monocarbamide dihydrogen sulfate (Gunsmoke®) at 187 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 7.3 g ai ha^{-1}
	Mar 26	W	Bromoxynil + pyrasulfotole (Huskie®) at 250 g ai ha^{-1}
			Thifensulfuron + tribenuron methyl (Affinity® BroadSpec) at 18.2 g ai ha^{-1}
			Mesosulfuron-methyl (Osprey®) at 15.6 g ai ha^{-1}
			Penetrant (Liberate®) at 438 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 1.8 g ai ha^{-1}
	Jul 28	W/B/C	Paraquat dichloride (Cyclone™ SL 2.0) at 2236 g ai ha^{-1}
2017	Mar 19 [a]	B/C	Glyphosate (Roundup Power Max®) at 1549 g ai ha^{-1}
			Water conditioning agent (Choice®) at 233 g ai ha^{-1}
			Penetrant (Liberate®) at 467 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 7.3 g ai ha^{-1}
	Mar 31	W	Bromoxynil + pyrasulfotole (Huskie®) at 250 g ai ha^{-1}
			Mesosulfuron-methyl (Osprey®) at 15.6 g ai ha^{-1}
			Penetrant (Liberate®) at 467 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 11 g ai ha^{-1}
	May 23	B	Bromoxynil + pyrasulfotole (Huskie®) at 268 g ai ha^{-1}
			Penetrant (Liberate®) at 467 g ai ha^{-1}
			Foam suppressant (Unfoamer®) 9.1 g ai ha^{-1}
	Aug 20	W/B/C	Paraquat dichloride (Gramoxone® SL 2.0) at 2660 g ai ha^{-1}
			Monocarbamide dihydrogen sulfate (Gunsmoke®) at 561 g ai ha^{-1}
			Penetrant (Liberate®) at 701 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 13.6 g ai ha^{-1}
2018	Feb 13[a]	B/C	Glyphosate application (Roundup Power Max®) at 1549 g ai ha^{-1}
			Monocarbamide dihydrogen sulfate (Gunsmoke®) at 374 g ai ha^{-1}
			Penetrant (Liberate®) at 467 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 7.3 g ai ha^{-1}
	Apr 9	W	Bromoxynil + pyrasulfotole (Huskie®) at 250 g ai ha^{-1}
			Mesosulfuron-methyl (Osprey®) at 15.6 g ai ha^{-1}
			Penetrant (Liberate®) at 467 g ai ha^{-1}
			Foam suppressant (Unfoamer®) at 9.1 g ai ha^{-1}
	May 19	B	Bromoxynil + pyrasulfotole (Huskie®) at 250 g ai ha^{-1}
			Penetrant (Liberate®) at 292 g ai ha^{-1}
			Foam suppressant (Unfoamer®) 0.5 g ai ha^{-1}

[a] This application was performed before seeding the crops.

2017 and 2018. All plots were seeded when moisture conditions were appropriate with two passes of a 3-m wide Seed Hawk air drill (Langbank, SK, Canada) in all years. Openers are a modified, ultra-narrow knife-type on 30 cm row spacing. The drill has a piston pump for metering liquid fertilizer in direct relation to ground speed through a ground drive system. Fertilizer was banded at seeding about 5 cm below and to the side of the seed row as a solution of 79% urea-ammonium nitrate and 21% ammonium thiosulfate to give rates of 61 kg N ha^{-1} and 12 kg S ha^{-1} (0.79 kg of product in 167 l ha^{-1}). University guidelines for N fertility were based on expected yields and pre-plant nitrate soil tests (Wysocki et al., 2007). Nitrogen fertilizer rates for winter wheat were increased over the recommended rate suggested by fall samples to compensate for winter precipitation moving nitrate deeper in the soil profile. For spring barley and spring carinata, the N application rate recommended was also increased to compensate for immobilization, due to high straw levels of previous winter wheat that temporarily reduces the amount of available N in the soil. Given the direction of these adjustments, the N applied to these winter and spring crops was the same. Harvest of W and B plots was performed using a Wintersteiger Delta combine with a top sieve of 9–10 mm in mid-July except B in 2017 that was 31 July. Carinata plots were harvested with the same machine at physiological maturity but using a top sieve of 5 mm.

2.3. Data collection

To evaluate the effect of the three cropping systems on the weed density and cover, 16 sampling frames (1 m × 0.5 m) were placed in each seeded plot: four in the weedy sub-plot, four in the weed-free sub-plot, and eight in the general area. Sampling frames were constructed from 1.25 cm diameter PVC pipe. All plots were sampled three times during the growing season: early season at beginning of weed competition (mid-March, tillering), mid-season at peak crop growth (end of May, flowering), and late-season at crop maturity (end of June, harvest). Therefore, the number of sampling frames per year was 576. At each sampling time, percent cover of each weed species was estimated visually within each frame. Density (plants m^{-2}) per weed species was also determined by counting the number of plants in each frame. Before combine harvest of the plots, the standing wheat in each frame was collected by destructive sampling by hand and bundled. Bundles of wheat were then threshed with an Almaco Vogel Plot Thresher and the resulting grain was cleaned and weighted for yield determination.

2.4. Statistical analysis

A generalized linear mixed model (GLMM) was used to evaluate differences in density and cover of total weeds, broadleaf weeds, and grass weeds among the three cropping systems. Mixed models allowed for incorporation of different levels of pseudo-replication inherent to plot sampling. In the GLMM analysis, the effect of cropping system, weedy and general areas, and their interaction were entered as fixed effects. Plot was included as a random effect. Prior to this analysis, the year effect was included as a fixed factor and evaluated. However, due to highly significant differences among years, analyses were made separately for each year to facilitate interpretation of results. A negative binomial distribution of errors was used for variables in 2015 and grass weed density and cover in 2016, 2017, and 2018 whereas a Poisson distribution was used for the broadleaf and total weed density and cover in 2016, 2017 and 2018. In all models, assumptions of equal variances and normal distribution of residuals were evaluated graphically. These analyses were implemented with glmer function of lme4 package (Bates et al., 2015) in the R program v. 3.3.2 (R Core Team, 2016).

Non-parametric multivariate analysis of variance (PERMANOVA) was conducted in the vegan package (Oksanen et al., 2017) to study significant differences in weed community among the W plots of the different cropping systems. Species abundance (i.e., density) was square-root transformed (Hellinger transformation) and a resemblance matrix constructed based on the Bray Curtis dissimilarity index. Cropping system, year, sampling, and cropping system × year and cropping system × sampling interactions were used as factors. Pairwise contrasts were performed when significant differences were found with the pairwiseAdonis package (Martinez Arbizu, 2017). The indicator value with the “indval” function of the labdsv package (Roberts, 2016) was calculated to identify weed species that could be indicative of each crop in the different cropping systems.

The Spearman’s correlation coefficient was used to reveal potential relationships between W yield, and weed density or cover per year at different sampling times. Non-linear mixed models (NLMM) were used to study W yield response to weeds in relation to cropping systems. Two models were tested, the hyperbolic model described by Cousens (1985) and a negative exponential model. The Cousen’s model presented problems to converge and non-significant parameters in some occasions. Consequently, the non-linear model selected was a negative exponential model [Eq. (1)]:

$$Y = Y_o e^{-cX} \quad (1)$$

where Y is yield (kg ha^{-1}), Y_o is yield in absence of weeds (kg ha^{-1}), X is either weed density (plants m^{-2}) or weed cover (%), and c is the rate of reduction crop yield reduction as weed abundance (i.e., X) increases. The NLMM was used to identify differences in model parameters (Y_o and c) between cropping systems. These analysis were performed for the first sampling in the weedy area and implemented with nlme package (Pinheiro et al., 2017) in the same software.

3. Results

The weed community in the experiment comprised 19 different species and was dominated by tumble mustard (*Sisymbrium altissimum* L.), downy brome (*Bromus tectorum* L.), prickly lettuce (*Lactuca serriola* L.), volunteer wheat, and Russian thistle (*Salsola tragus* L.) with an average percentage of presence greater than 10% (Table 2 and Supplemental Table 2). Weed composition varied with year. Downy brome and prickly lettuce increased over time while Russian thistle and kochia (*Kochia scoparia* (L.) Schrad.) decreased. Some species disappeared [lambsquarter (*Chenopodium leptophyllum* (Moq.) Nutt. ex S.Wats)] while others appeared [coast fiddleneck (*Amsinckia menziesii* (Lehm.) A. Nels. & J.F. Macbr. var. intermedia), flixweed (*Descurainia sophia* (L.) Webb. ex Prantl), panicle willowweed (*Epilobium brachycarpum* K. Presl), and prostrate knotweed (*Polygonum aviculare* L.)] after 2015. Others appeared in only one of the years [horseweed (*Conyza canadensis* (L.) Cronq.) and henbit (*Lamium amplexicaule* L.)]. Density of weed species varied with cropping system (Table 2 and Supplemental Table 2).

3.1. Effect of year and cropping system on weed density and cover.

Effect of year significantly influenced ($p < 0.001$) total weed cover and density, grass weed cover and density, and broadleaf weed cover and density. Weed infestation increased with each year (Table 2, Supplemental Table 2). In 2015, scarcity of grasses prevented statistical comparison among cropping systems and no differences were found for broadleaf weed cover and density. However, in remaining years, cropping system, area (related to weed control), and their interactions differed for total, broadleaf, and grass weeds (Table 3, Supplemental Table 3, Fig. 1, Supplemental Fig. 2, Supplemental Table 4). In general, total and broadleaf weeds were similar because the latter contributed the most to total infestation. Infestation was generally higher in the weedy subplots than in the general area due to chemical applications (Table 1) that likely reduced the seedbank. For grasses, a difference between those areas was not found. The low herbicide effect seen may reflect a resistance of downy brome to group two herbicides such as the mesosulfuron-methyl, downy brome germination flushes after herbicide treatment, or both.

In 2017, when a complete rotation had occurred (Supplemental Table 1), density of total and broadleaf weeds was lower in the general area of the F/W/B system compared to the other cropping systems. In addition, the F/W system showed higher grass weed infestation in both areas (weedy and general) than both 3-yr systems indicating positive weed control from increased crop diversification. In 2018, when two complete rotations had occurred, total weed infestation was higher in F/W than in both 3-yr systems except for total weed cover in F/W/B in the weedy sub-plots, which was not significantly different from that in F/W. Similarly, this year, grass and broadleaf weeds in each 3-yr system were lower than in F/W for both areas, weedy and general.

3.2. Effect of year and cropping system on weed community

Year, sampling time, and cropping system × year interaction significantly affected weed community composition in W, but not cropping system (Table 4). Pairwise comparisons showed weed communities to significantly differ in 2017 between F/W/B and F/W ($p = 0.013$), and between F/W/C and F/W ($p = 0.013$), but not between F/W/B and F/W/C.

When significant differences were found among cropping systems, indicator value analysis was used to identify the most frequent weeds present. In 2017, downy brome was the most important species characterizing W in the F/W system, as well as panicle willowweed, whereas prickly lettuce was important in F/W/B (Table 5). Russian thistle was the only species related with carinata (spring oilseed).

3.3. Effect of cropping system on wheat yield

A significant negative correlation was found in all growing seasons between weed variables and W yield, especially for years 2017 and 2018 (Table 6).

The negative exponential mixed model for the first sampling performed for 2017 and 2018 found no differences in W yield between cropping systems when weeds were not present in 2017 (Tables 7 and 8). However, greater W yields from the F/W/B system were found in 2018 (Y_o in Table 7; Fig. 2). In 2017, parameter c indicated that the yield reduction rate when weeds are present was significantly greater in F/W/C than that in F/W (Table 7, Table 8, Fig. 2). In contrast, in 2018, the reduction rate was higher in F/W/B compared to F/W. Therefore, weeds in F/W/C may have been more competitive than in other cropping systems early in 2017 whereas weeds were more competitive in F/W/B in 2018.

4. Discussion

Downy brome was the most dominant grass species found in this

Table 2
Density (plants m^{-2} ± SD) of weed species and presence (number of frames relative to the total number of frames in which a species is present) in the winter wheat (W) plots of three cropping systems in 2017 and 2018.

		2017				2018[1]			
		Cropping system (Plants m^{-2} ± SD)				Cropping system (Plants m^{-2} ± SD)			
Scientific name	Common name	F/W	F/W/B	F/W/C	% Pres.	F/W	F/W/B	F/W/C	% Pres.
Winter annuals									
Sisymbrium altissimum L.	Tumble mustard	13.0 ± 21.4	13.5 ± 22.7	18.7 ± 31.5	55.3	22.2 ± 39.5	14.7 ± 25.3	11.7 ± 20.6	62.9
Bromus tectorum L.	Downy brome	7.3 ± 13.9	1.0 ± 2.4	3.0 ± 15.7	42.8	13.2 ± 23.6	1.2 ± 2.9	1.2 ± 3.7	63.2
Lactuca serriola L.	Prickly lettuce	1.5 ± 2.7	2.3 ± 6.3	2.2 ± 5.7	43.1	3.5 ± 5.8	2.6 ± 4.7	2.6 ± 4.2	48.3
Triticum aestivum L.	Volunteer wheat	0.23 ± 1.2	0.3 ± 1.7	0.2 ± 0.7	11.1	0.7 ± 2.2	0.5 ± 1.3	0.5 ± 1.6	21.5
Avena fatua L.	Wild oat	0.02 ± 0.2	0	0	0.5	0	0.1 ± 0.4	0.02 ± 0.2	0.7
Brassica carinata A. Braun	Volunteer canola	0.2 ± 0.9	0.4 ± 1.7	0.3 ± 1.4	8.6	0.03 ± 0.3	0.4 ± 1.8	0.5 ± 2.2	9.4
Secale cereal L.	Cereal rye	0.03 ± 0.3	0.1 ± 0.4	0.1 ± 0.3	2.6	0.02 ± 0.2	0.03 ± 0.4	0.03 ± 0.4	1.0
Amsinckia menziesii (Lehm.) A. Nels. & J.F. Macbr. var. *intermedia*	Coast fiddleneck	0.01 ± 0.1	0.02 ± 0.2	0.01 ± 0.1	0.9	0	0	0.1 ± 0.3	1.0
Descurainia sophia (L.) Webb. ex Prantl	Flixweed	0.1 ± 0.4	0	0	0.9	0	0.2 ± 1.2	0.02 ± 0.2	2.1
× *Triticosecale* Wittm. ex A. Camus.	Volunteer triticale	0.1 ± 0.7	0.01 ± 0.1	0	0.7	0.2 ± 1.0	0.1 ± 0.3	0	2.8
Lamium amplexicaule L.	Henbit	0	0.02 ± 0.2	0.01 ± 0.1	0.7	0	0	0	0.0
Summer annuals									
Salsola tragus L.	Russian thistle	0.04 ± 0.4	0.03 ± 0.3	0.2 ± 1.2	2.1	0.1 ± 0.6	0.1 ± 0.6	0	1.4
Epilobium brachycarpum K. Pres	Panicle willowweed	1.2 ± 5.7	0.2 ± 0.8	0.2 ± 1.1	10.9	0.4 ± 1.1	0.2 ± 0.8	0.2 ± 0.7	9.7
Kochia scoparia (L.) Schrad.	Kochia	0.01 ± 0.1	0	0.1 ± 1.5	1.2	0.1 ± 0.6	0	0	0.7
Amaranthus sp.	Pigweed	0.03 ± 0.4	0.02 ± 0.3	0.02 ± 0.2	0.9	0	0	0	0.0
Chenopodium leptophyllum (Moq.) Nutt. ex S.Wats[2]	Lambsquarter	0	0	0	0.0	0	0	0	0.0
Conyza canadensis (L.) Cronq.	Horseweed	0.01 ± 0.1	0	0.02 ± 0.2	0.7	0	0	0	0.4
Draba verna L.[2]	Spring whitlowgrass	0	0	0	0.0	0	0	0	0.0
Polygonum aviculare L.	Prostrate knotweed	0	0	0	0.0	0	0	0.2 ± 1.8	0.7
Biennials									
Tragopogon dubius Scop.	Western salsify	0.03 ± 0.3	0	0	0.7	0.1 ± 0.3	0	0	0.7
Total		23.8 ± 30.5	17.8 ± 26.7	25.2 ± 37.9	78.9	40.8 ± 48.8	19.9 ± 26.8	16.6 ± 23.3	91.0

[1]Average value in 2018 were based only on first and third samplings.
[2]C. leptophyllum and D. verna were only present in the previous years of the experiment (see Supplemental Table 2).

Table 3
Effects of cropping system, area, and their interaction over total weed cover and density, broadleaf weed cover and density, and grass weed cover and density in 2017 and 2018. Chi-squared values and degrees of freedom (df) were derived by means of generalized linear mixed models.

	df	Total weed cover	Total weed density	Broadleaf weed cover	Broadleaf weed density	Grass weed cover	Grass weed density
2017							
Cropping system	2	1.7	0.2	3.7	0.3	3.7	5.8.
Area	1	0.4	77.6 ***	0.2	83.3 ***	0.4	0.1
Cropping system × Area	2	53.5 ***	136.0 ***	52.0 ***	106.1 ***	0.2	0.1
2018							
Cropping system	2	12.4 **	28.9 ***	8.6 *	22.1 ***	6.9 *	12.1 **
Area	1	176.4 ***	276.9 ***	249.2 ***	494.5 ***	1.5	0.8
Cropping system × Area	2	8.9 *	27.7 ***	3.4	6.5 *	1.9	3.3

[a]Significant codes for p-values obtained after the GLMMs: · $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

study in agreement with Schillinger (2016) in eastern Washington. Tumble mustard was predominant in the weedy areas where no chemical was applied but it is normally controllable with herbicides, which apparently explains its absence in the general areas. Variability in environmental conditions among years was the most important factor influencing grain yield, weed abundance and diversity. Soil moisture greatly influences seed germination in semi-arid environments (Blackshaw et al., 2001). Total precipitation varied with year (Supplemental Fig. 1) with 2017 being the wettest. Precipitation could explain differences in crop and weed densities such as Russian thistle, which is not favored in wetter years (Schillinger, 2016).

4.1. Effect of cropping systems on weeds

The significant year × cropping system interaction suggested the importance of environmental conditions in determining the weed community assembly (Table 4). A decrease in grass cover and density was observed in 2017 and 2018 when a spring crop was present in the rotation and plots had gone through one and two complete rotation cycles. Crop rotation is known to reduce weed problems (Liebman and Dyck, 1993; Nichols et al., 2015) and thus one would expect that cropping system was an effective control measure. The effects of crop rotation might take a few years (Bellinder et al., 2004) or longer (Bàrberi, 2002) to influence the weed seedbank (Ball, 1992). Dryland cropping systems that include fallow are useful for controlling annual grasses in W as found in the Great Plains (Lyon and Baltensperger, 1995). By including a spring crop with or without fallow, the period between W crops can be lengthened for controlling grass weed (Daugovish et al., 1999).

Downy brome was the predominant grassy weed in all cropping systems. However, its abundance was greatly reduced in 3-yr cropping systems (F/W/B and F/W/C) compared to F/W (Fig. 1, Supplemental

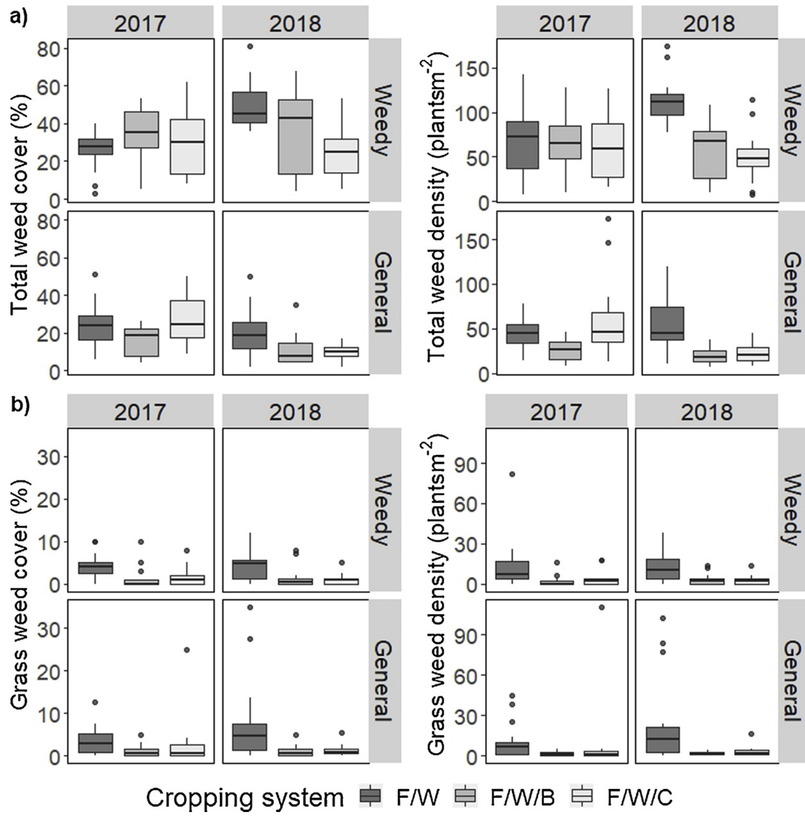

Fig. 1. Total weed density and cover (a) and grass weed density and cover (b) observed in the weedy and general areas in three cropping systems in 2017 and 2018.

Fig. 2, and Supplemental Table 4) thus indicating that diversifying the F/W system with a spring crop can provide a break-effect on the life cycle of this winter annual species. Downy brome germination occurs mainly in the fall with first rains and to a lesser extent in the early spring (Lyon et al., 2015). The establishment of a spring crop could eliminate emerged seedlings of downy brome by means of pre-emergence herbicide applications, tillage operations, or crop sowing. Any late emerged seedling could not thrive due to lack of vernalization and crop competition. Moreover, grass infestations of downy brome could have been reduced because of a potential allelopathic effect of B and C on weeds. Bouhaouel et al., (2015) showed an allelopathic effect of B on a similar species of brome (*Bromus diandrus* L.) and in annual ryegrass (*Lolium rigidum*). Asaduzzaman et al. (2015), working with *Brassica napus,* a similar species to C, found an alellopathic effect on annual ryegrass as well.

Three-year cropping systems that included a spring crop, also significantly reduced broadleaf weeds, particularly in 2018 (Fig. 1, Table 3). Though, in that year, no significant differences were found in the weed community for the 3-yr cropping systems. In 2017, prickly lettuce resulted as a characteristic species according to the indicator value of W plots in the F/W/B cropping system. Prickly lettuce could have occupied the niche abandoned by downy brome resulting from control by B. Downy brome and prickly lettuce are both winter annuals, but prickly lettuce behaves as a winter or summer annual in eastern Oregon thus giving it greatly extended emergence (Weaver et al.,

Table 5
Species with a significant Indicator Value for year 2017 in the weedy area. Frequency is the number of times the species was present among samples.

Species	Crop (Cropping system)	Frequency	Indicator value	p-value
Downy brome	W (F/W)	38	0.683	0.001
Panicle willowweed	W (F/W)	15	0.417	0.017
Prickly lettuce	W (F/W/B)	47	0.416	0.034
Russian thistle	C (F/W/C)	18	0.368	0.003

Table 6
Spearman correlation coefficient between crop yield (kg ha^{-1}) and weed density (plants m^{-2}) or percentage of cover (%) for the first and third sampling times in the weedy and weed free area.

	Early season		Late season	
Year	Density	Cover	Density	Cover
2015	−0.227*[a]	−0.179.	−0.255*	−0.319**
2016	−0.465***	−0.411***	−0.458***	−0.527***
2017	−0.781***	−0.772***	−0.805***	−0.762***
2018	−0.860***	−0.877***	−0.880***	−0.883***

[a] Significance codes for p-values: · $p < 0.1$; * $p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table 4
PERMANOVA results for the year, sampling, and cropping system effect and their interactions on weed community composition in the weedy area.

	Cropping system	Sampling	Year	Cropping system × Year	Cropping system × Sampling
df	2	2	3	6	4
Pseudo-F	1.01	6.76***	23.40***	2.01**	0.88

df = degrees of freedom. Significant codes for p-values obtained after PERMANOVA analysis: ·$p < 0.1$; * $p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table 7
Non-linear (negative exponential) mixed model (NLMM) parameters (Y_o and c) and their significance for the relationship between crop yield and weed cover, and crop yield and weed density in three cropping systems for the first sampling. Y_o is crop yield when there is no weed presence; c is the rate of crop yield reduction.

Models	Parameters	2017 Estimate	2017 p-value	2018 Estimate	2018 p-value
Crop yield in response to weed cover	Y_0: Intercept [b]	4221	**0.000** ***	1995	**0.000** ***
	Y_0: Cropping system (F/W/B)	−326	0.574	501	**0.053.**
	Y_0: Cropping system (F/W/C)	589	0.313	−25	0.921
	c: Intercept [c]	0.06	**0.000** ***	0.05	**0.000** ***
	c: Cropping system (F/W/B)	−0.02	0.333	0.02	0.445
	c: Cropping system (F/W/C)	0.07	**0.063**	0.004	0.802
Crop yield in response to weed density	Y_0: Intercept [b]	4230	**0.000** ***	1995	**0.000** ***
	Y_0: Cropping system (F/W/B)	−345	0.547	562	**0.013** *
	Y_0: Cropping system (F/W/C)	578	0.317	−45.8	0.836
	c: Intercept [c]	0.03	**0.001** ***	0.03	**0.001** **
	c: Cropping system (F/W/B)	−0.01	0.356	0.03	**0.034** *
	c: Cropping system (F/W/C)	0.04	**0.092.**	0.001	0.917

[a]Significant codes for p-values obtained after the NLMMs: · $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.
[b] Intercept is the expected mean value of Y_0 when all predictor variables = 0. Here the intercept refers to F/W cropping system.
[c] Intercept is the expected mean value of c when all predictor variables = 0. Here the intercept refers to F/W cropping system.

Table 8
Average winter wheat (W) yield (kg ha^{-1} ± SD) in three cropping systems [Fallow (F)/W; F/W/Barley (B); F/W/Carinata (C)] between 2015 and 2018 for weedy area, weed-free area, and general area.

Year	F/W	F/W/B	F/W/C
	Weedy Area		
2015	2507 ± 1341	2635 ± 692	1882 ± 743
2016	1462 ± 661	1817 ± 1025	1452 ± 758
2017	1259 ± 1283	1171 ± 843	857 ± 679
2018	172 ± 208	527 ± 469	622 ± 497
	Weed-Free Area		
2015	3092 ± 906	2596 ± 633	2537 ± 569
2016	2062 ± 479	2399 ± 862	2247 ± 516
2017	4238 ± 1358	4025 ± 1620	4820 ± 1236
2018	1996 ± 647	2573 ± 591	1968 ± 119
	General Area		
2015	2756 ± 962	2361 ± 939	1890 ± 610
2016	1865 ± 722	2452 ± 666	2319 ± 795
2017	3416 ± 1159	4087 ± 621	3661 ± 714
2018	2198 ± 719	2363 ± 936	1999 ± 488

2006). Therefore, seedlings emerging in the spring could benefit from environmental conditions provided by B. Because a shift in weed flora could occur, special attention should be given to introducing different crops into a cropping system (Andersson and Milberg, 1998). Though prickly lettuce was a characteristic species in F/W/B in 2017, it did not contribute the most to total broadleaf weeds in that cropping system. Tumble mustard contributed 81% to total broadleaf weed density but did not cause cropping systems to significantly differ in that year (Table 3). However, after two cycles were completed by 2018, tumble mustard that had been 90% of total broadleaf weeds was reduced in 3-yr systems compared to the 2-yr system. Since tumble mustard is a winter annual species, a break-effect of this specie's life cycle could have occurred. Flixweed, a species similar to tumble mustard, is also associated with F/W systems (Blackshaw et al., 2001).

Russian thistle is a summer annual that germinates late in the season and tends to be more frequent in spring crops than winter crops (Moyer et al., 1994). In Alberta, this species increased in wheat-canola rotations (Blackshaw et al., 2001, 1994). The fact that it was characteristic of C but not B might be attributable to greater competitiveness of the latter. In this study, the carinata canopy was less dense than that of B allowing better development of Russian thistle plants. Russian thistle was found to have a low tolerance to competition, growing better in crop- and

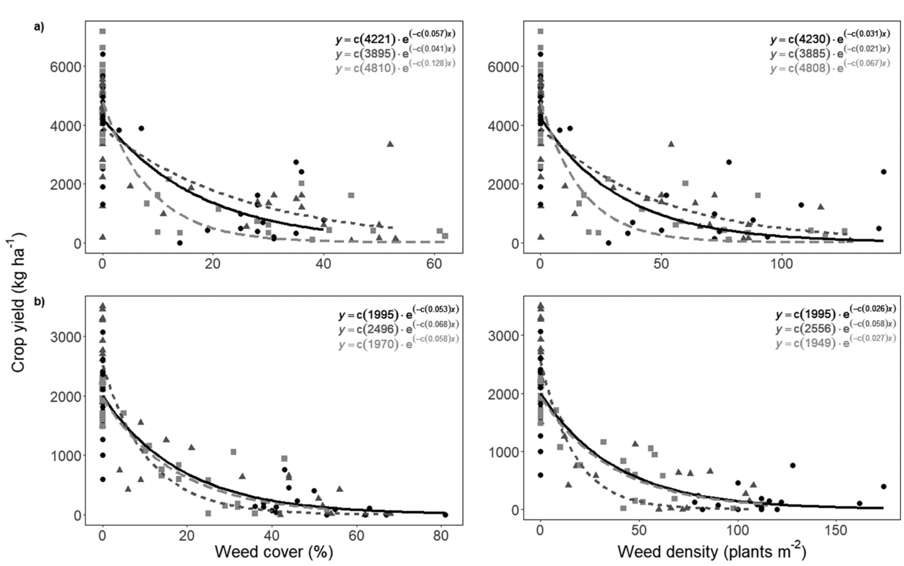

Fig. 2. Relationship between winter wheat yield (kg ha^{-1}) and early sampling weed density (plants m^{-2}) and weed cover (%) in 2017 (a) and 2018 (b).

weed-free areas (Young, 1986) as well as after harvest.

4.2. Effect of crop rotations on wheat yield

Winter wheat yields were higher in the F/W/B system in 2018. Smiley and Machado (2009) found a reduction of soil pathogens that infect wheat roots with preceding barley. In this study, F/W and F/W/C did not significantly differ in W yield in contrast to other studies reporting improvement in W yield when diversifying with oilseed crops (Angus et al., 2011; Bushong et al., 2012; Gan et al., 2003; Johnston et al., 2002). This difference with other studies could be due to lower weed competition under the influence of oilseed crops. Brassica root exudates contain allelopathic compounds that may act as bioherbicides (Asaduzzaman et al., 2015; Brown and Morra, 1995). The F/W/C system experienced a greater decrease in wheat yield compared to F/W with the same amount of weed infestation in 2017 (Table 7, Fig. 2), possibly because weeds benefited from the enhanced accumulation of mineral N following a *Brassica* crop (Ryan et al., 2006). *Brassica* cultivars differ in their ability to suppress weed infestations (Asaduzzaman et al., 2014; Beckie et al., 2008) and it is possible that the allelopathic effect, mentioned previously, do not extend to weeds in following crops. Nevertheless, when analyzing weed variables in the third sampling (Supplemental Fig. 3), significant differences in the rate of yield reduction were not observed. Weeds in 2018 appeared to be more competitive in F/W/B than in 2017 making it difficult to elucidate the effect of weeds on wheat yields in the different cropping systems. More years of data would be necessary to clarify the effect of weed-crop competition as shown in long-term experiments (Ryan et al., 2009).

5. Conclusions

Compared to F/W, including either B or C in 3-yr rotations with W significantly reduced density and cover of grass weeds (composed mostly of downy brome) after one cropping cycle in 2017 and two cycles in 2018. However, reduction of total weed cover and density was only achieved in the last year of the study. Downy brome was a characteristic species of the F/W cropping system due to the lack of a break-effect from a spring crop to control this species. Control of downy brome might cause other generalist broadleaf weeds such as prickly lettuce to become more present in the F/W/B system. In our study, W yields were greater after two complete cycles of the F/W/B system compared with the F/W system. Future long-term experiments will help clarify the effect of B on weed communities and confirm benefits to W yields.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2018.12.017.

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